MATTERS ARISING

Giant solar flares in Antarctic ice

ROOD *et al.*[1] have discovered four prominent 'spikes' in a long time record (circa 1150 to the present) of the NO_3^- concentration inside an Antarctic ice core. These four spikes rise 2–3 times higher than the upper envelope of a fluctuating background level of 0–20 $\mu g\,l^{-1}$ that has been plausibly attributed to the action of high-energy solar radiation (photons and particles) impinging on the Earth's upper atmosphere and ionizing N_2, thereby leading to various chains of chemical reactions that culminate in the formation of NO_3^-, some of which is transported, within a few weeks or months, to Antarctica[1]. According to three alternative chronologies provided by Rood *et al.*, the estimated dates of the four NO_3^- spikes lie within the intervals given in Table 1. Three of these dates have been tentatively associated by the same authors with the galactic supernovae of 1604, 1572 and 1181. At the outset, they have rejected energetic particles from the supernova explosion as a possible source of ionization of the terrestial N_2 because galactic magnetic fields would have greatly delayed and diffused the particles on their way to Earth. Instead , they have shown that photons of energy $\gtrsim 10$ keV are required. Unfortunately, as they admitted, the total energy requirements are difficult to meet, and the matching of dates with historical supernovae is not perfect.

As an alternative explanation, I suggest that the necessary ionizing radiation could have come from unusually powerful solar flares. These flares would be expected to have occurred preferentially during periods when the Sun was generally most active, that is around the times of the largest maxima in the solar cycle. Two good indices of solar activity are available: for the years elapsed since 1700, there are both sunspot numbers[2] and auroral numbers[3]; for earlier years auroral statistics[3–6] are preferred because the sunspot record (mostly from the Far East) is very sporadic[7]. Despite some incompleteness of the record before 1700, the main trends in the statistics are quite unmistakable (see refs 3 and 5).

The intervals of time in which the largest auroral and sunspot maxima occurred are listed in Table 1, where earlier dates are given only to the nearest half-decade. These intervals of time correlate very well with the known epochs of the NO_3^- spikes. Only in one case is it necessary to recognize that episodes of solar flaring need not occur (as they have not always occurred in modern times) precisely at times of maximum auroral or maximum sunspot numbers. This therefore gives some flexibility in the possible dates of the giant solar flares that is not available in the case of the supernova hypothesis. However, there are no NO_3^- spikes in the years around 1778 and 1957, at which times solar activity was also at a peak. Nevertheless, given the rarity of the proposed flaring events, this absence could simply be a product of statistical fluctuations. Also the Sun may now be somewhat different physically from its state before the long Maunder minimum in 1645–1715 (ref. 2).

According to Table 1, very large solar maxima seem to recur in cycles of ~200 yr, as Schove[4] originally noted. In the background NO_3^- data, there is also some evidence of the Maunder minimum and of the normal 11-yr solar cycle[1]. Bauer[8] estimated that the background concentration could vary by a factor of two during the 11-yr cycle. To extend this further, I consider the largest solar flares in modern times. These have importance class 3+ or 4 and emit $E_{32}\times 10^{32}$ erg of high-energy radiation (photons and particles), where $E_{32}\sim 1$–2 (ref. 9). The Earth intercepts $4\times 10^4\,E_{32}$ erg cm^{-2} of this. According to Rood *et al.*[1], the energy flux needed to produce a NO_3^- concentration of $20\,C_{20}\,\mu g\,l^{-1}$ near the South Pole is ~ $1\times 10^5\,C_{20}$ erg cm^{-2} yr^{-1}. Since $C_{20}\leqslant 1$, only one or two major flares per year is sufficient to produce all of the background NO_3^-. It is therefore not unreasonable to suppose that, every couple of hundred years or so, a giant flare, perhaps 2–3 times more intense than ordinary major flares, erupts on the Sun. An alternative possibility is that a very rapid succession of major flares of the ordinary type takes place. An event of this type may still develop during the current maximum of solar activity.

The Antarctic ice-core measurements are apparently now being pushed to deeper levels than before[1]. Much older NO_3^- spikes may therefore be discovered. One immediate prediction of the solar flare hypothesis is the possibility (though no more than that) of a spike occurring around the year 1000, a time of heightened auroral activity[3–5]. On the other hand, a very bright supernova also appeared in 1006, as Rood *et al.* pointed out. But, fortunately, an *experimentum crucis* to discriminate between the two hypotheses can be made for the middle of the eleventh century, a time of profound auroral quiet but, equally importantly, of a brilliant supernova, the Crab explosion of 1054.

Table 1 Dates of the largest maxima in the Antarctic concentration of NO_3^- and in solar activity indices

Largest NO_3^- maxima	Largest solar maxima
1130–1160	1120–1140
1300–1340	1360–1375
1590–1600	1565–1585
1610–1620	1605–1630
–	1778–1788
–	1947–1959

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Magnetic fields and the solar constant

THOMAS[1] has suggested that changes in the magnetic flux content of the convection zone produces changes in radius. However, his calculations did not include the effect of structural changes in the superadiabatic region on the bulk of the convection zone. Theoretical studies[2–4] have shown that solar luminosity fluctuations can result from small structure adjustments in the convection zone, and can occur on time scales shorter than 1 yr. Such fluctuations are of interest in studies of the terrestrial climate.

The previous calculations have forced these structural changes by assuming a time-dependent mixing length. When the mixing length (physically the convective efficiency) changes, adjustments in the structure occur rapidly in the superadiabatic region, and in turn the bulk of the convection zone adjusts to maintain hydrostatic equilibrium. The result is a temporary luminosity change[3]. Any mechanism which affects the structure of the superadiabatic region will cause such a luminosity fluctuation. The effect of magnetic pressure changes on the superadiabatic region is described here.

We began by including a global magnetic pressure term in a stellar structure code. If the flux is assumed to be concentrated in vertical flux tubes, the pressure at a given radius (r) is given by

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